The influence of the magnetic fields on v_2 in HIC at RHIC and LHC energies

4^{th} Workshop on Chirality, Vorticity and Magnetic Field in HIC

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in collaboration with:

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Special thanks to: F. Becattini and A. Beraudo.

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FIAS Frankfurt Institute for Advanced Studies

H-QM Helmholtz Research School Quark Matter Studies

HGS-HIRe for FAIR Helmholtz Graduate School for Hadron and Ion Research

About this *exploratory* work:

- Aim 1: explore the possible effects of $\vec{B}$ on v_2 at RHIC and LHC energies
- Aim 2: evaluate which are the most significant parameters to focus on
- Aim 3: find constraints on the properties of the medium
- Method: ideal 3D+1 MHD simulations with ECHO-QGP using Glauber i.c.
- We focus on: impact parameter, σ (σ_χ), $T_{f.o.}$
- Strengths: dynamical evolution of the magnetic field coupled with the fluid
- Weaknesses: no resistivity, no charge distinction in produced particles, no hadronic rescattering

What is ECHO-QGP

ECHO-QGP derives from the Eulerian Conservative High-Order astrophysical code for general relativistic magnetohydrodynamics, developed by L. Del Zanna.

(Del Zanna, Zanotti, Bucciantini, and Londrillo, A&A 473 (2007))

A collaboration lead by F. Becattini adapted ECHO-QGP to run second order dissipative hydrodynamical simulations of heavy ion collisions, including the computation of particle spectra following the Cooper-Frye prescription.

Del Zanna, Chandra, Inghirami, Rolando, Beraudo, De Pace, Pagliara, Drago, and Becattini, Eur.Phys.J. C 73 (2013)

Floerchinger, Wiedemann, Beraudo, Del Zanna, Inghirami, Rolando, PLB 735 (2014)

Becattini, Inghirami, Rolando, Beraudo, Del Zanna, De Pace, Nardi, Pagliara, Chandra, Eur. Phys. J. C 75 (2015)

Inghirami, Del Zanna, Beraudo, Haddadi, Becattini, Bleicher, Eur. J. Phys. C 76 (2016)

Website: http://theory.fi.infn.it/echoqgp/

The basis

The fundamental equations

Energy and momentum conservation: $d_\mu T^{\mu\nu} = 0$
Baryonic number conservation: $d_\mu N^\mu = 0$
Second law of thermodynamics: $d_\mu s^\mu \geq 0$
Maxwell equations: $d_\mu F^{\mu\nu} = -J^\nu \quad (d_\mu J^\mu = 0) \qquad d_\mu F^{\star\mu\nu} = 0$

The fundamental assumptions

- We neglect all dissipative effects
- We neglect polarization and magnetization effects
- We assume infinite electrical conductivity

The ideal RHMD energy-momentum tensor

Polarization and magnetization neglected

$T_f^{\mu\nu} = F^{\mu}{}_{\lambda} F^{\nu\lambda} - \frac{1}{4}(F^{\lambda\kappa}F_{\lambda\kappa})g^{\mu\nu}$

from Maxwell equations: $d_\mu T_{\mathrm{f}}^{\mu\nu} = J_\mu F^{\mu\nu}$

Dissipative effects neglected:

Eckart frame = Landau frame ⇒ single fluid u^μ $(u_\mu u^\mu = -1)$

Infinite electrical conductivity

Ohm's law: $J^\mu = \rho_{\mathrm{e}} u^\mu + j^\mu; \quad j^\mu = \sigma^{\mu\nu} e_\nu \Rightarrow e^\mu = 0$

Energy-momentum tensor $T^{\mu\nu}$

$T^{\mu\nu} = T_m^{\mu\nu} + T_f^{\mu\nu}$

Matter: $T_m^{\mu\nu} = (e+p)u^\mu u^\nu + p g^{\mu\nu}$

Electromagnetic field: $T_f^{\mu\nu} = b^2 u^\mu u^\nu + \frac{1}{2} b^2 g^{\mu\nu} - b^\mu b^\nu$

The energy momentum tensor components

Lorentz transformations from the laboratory to the comoving frame:
$e^\mu = (\gamma v_k E^k, \gamma E^i + \gamma \varepsilon^{ijk} v_j B_k)$
$b^\mu = (\gamma v_k B^k, \gamma B^i - \gamma \varepsilon^{ijk} v_j E_k)$ where:
ε_{ijk} is the Levi-Civita pseudo-tensor of the spatial three-metric
γ = Lorentz factor, $g_{ij} = \mathrm{diag}(1,1,1)$ or $g_{ij} = \mathrm{diag}(1,1,\tau^2))$
e and p are measured in the *comoving fluid frame*,
$\vec{E}$ and $\vec{B}$ are measured in the *laboratory frame*

Components of the energy-momentum tensor

Energy density $\mathcal{E} \equiv -T^0_0 = (e+p)\gamma^2 - p + \frac{1}{2}(E_k E^k + B_k B^k)$
Momentum density $S_i \equiv T^0_i = (e+p)\gamma^2 v_i + \varepsilon_{ijk} E^j B^k$
Stresses $T^i_j = (e+p)\gamma^2 v^i v_j + (p + \frac{1}{2}(E_k E^k + B_k B^k))\delta^i_j - E^i E_j - B^i B_j$

The evolution equations

Ideal Ohm'law in the laboratory frame

$e^\mu = 0 \;\Rightarrow\; E_i = -\varepsilon_{ijk} v^j B^k$

The evolution equations in conservative form

$$\partial_0 \mathbf{U} + \partial_i \mathbf{F}^i = \mathbf{S}$$

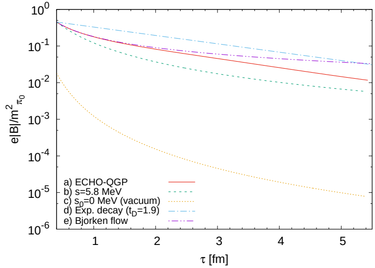
where

$$\mathbf{U} = |g|^{\frac{1}{2}} \begin{pmatrix} \gamma n \\ S_j \equiv T^0_j \\ \mathcal{E} \equiv -T^0_0 \\ B^j \end{pmatrix}, \quad \mathbf{F}^i = |g|^{\frac{1}{2}} \begin{pmatrix} \gamma n v^i \\ T^i_j \\ S^i \equiv -T^i_0 \\ v^i B^j - B^i v^j \end{pmatrix}, \quad \mathbf{S} = |g|^{\frac{1}{2}} \begin{pmatrix} 0 \\ \frac{1}{2} T^{ik} \partial_j g_{ik} \\ -\frac{1}{2} T^{ik} \partial_0 g_{ik} \\ 0 \end{pmatrix}$$

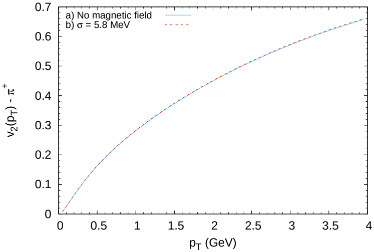
Time evolution of the magnetic field at the center of the grid

Eur. J. Phys. C 76 (2016)

2D+1 simulation of Au+Au collision at $\sqrt{s}_{\mathrm{NN}} = 200\ \mathrm{AGeV}$

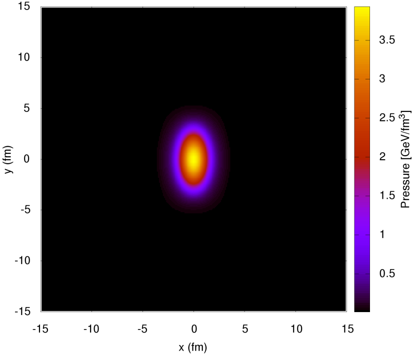


Magnetic field at x=y=0



Elliptic flow of positive pions

New 3D+1 simulations: initial conditions for pressure



Thermal pressure at $\tau = 0.4\,\mathrm{fm/c}$, Au+Au collision at $\sqrt{s_{\mathrm{NN}}} = 200\,\mathrm{AGeV}$ impact parameter b=12 fm.

3D+1 simulation in Milne coordinates
Geometrical Glauber initial conditions.
Almost all parameters as in:
Pang et al. - Phys. Rev. C 93, 044919

Parameter	RHIC	LHC
Ion	Au 197	Pb 208
$\sqrt{s_{\mathrm{NN}}}$ $(AGeV)$	200	2760
τ_0 (fm/c)	0.4	0.2
$T_{f.o.}$ (MeV)	154	154
ϵ_0 (GeV/fm^3)	55	413.9
$\sigma_{in.}$ (mb)	42	64
$\alpha_{bin.coll.}$	0.05	0.05
η_{flat}	5.9	7.0
σ_η	0.4	0.6

Initial conditions for $\vec{B}$: basic formula for point charge

Li, Sheng and Wang, Phys. Rev. C 94, 044903 (2016)

$$
\begin{aligned}
B_\phi(t,\mathbf{x}) &= \frac{Q}{4\pi}\cdot\frac{v\gamma x_T}{\Delta^{3/2}}\left(1+\frac{\sigma v\gamma}{2}\sqrt{\Delta}\right)e^{A},\\
B_r(t,\mathbf{x}) &= -\sigma_\chi\frac{Q}{8\pi}\cdot\frac{v\gamma^2 x_T}{\Delta^{3/2}}\cdot\left[\gamma(vt-z)+A\sqrt{\Delta}\right]e^{A},\\
B_z(t,\mathbf{x}) &= \sigma_\chi\frac{Q}{8\pi}\cdot\frac{v\gamma}{\Delta^{3/2}}\cdot\\
&\quad\left[\gamma^2(vt-z)^2\left(1+\frac{\sigma v\gamma}{2}\sqrt{\Delta}\right)+\Delta\left(1-\frac{\sigma v\gamma}{2}\sqrt{\Delta}\right)\right]e^{A}
\end{aligned}
$$

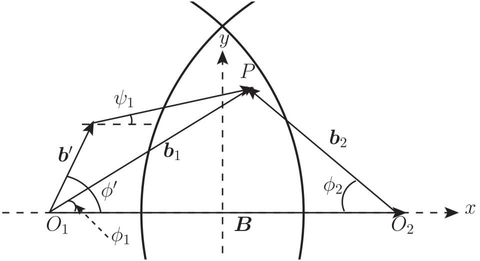
where: σ is the electric conductivity, σ_χ the chiral magnetic conductivity, $\Delta\equiv\gamma^2(vt-z)^2+x_T^2$, $A\equiv(\sigma v\gamma/2)[\gamma(vt-z)-\sqrt{\Delta}]$

Our initial conditions: formula for two colliding nuclei

The nuclei freely propagate into a medium with finite conductivity, before and after the collision. For each of them (uniformly charged disk approximation):

$$B_Z(x_-, b_1) = \int 2\sqrt{R_A^2 - b'^2}\rho\, B(x_-, |b_1 - b'|)(-\sin\psi_1 \hat{\boldsymbol{x}} + \cos\psi_1 \hat{\boldsymbol{y}}) d^2 b \quad (1)$$

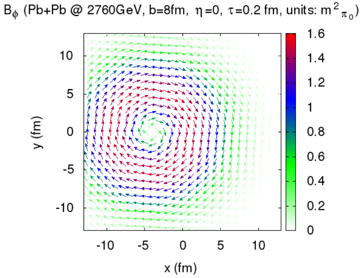
A similar expression holds for the other nucleus and the total magnetic field is the sum of the two.

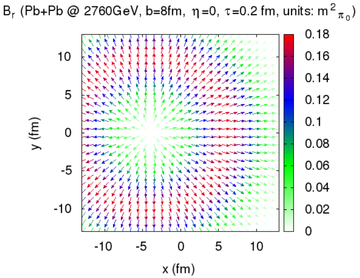


Tuchin - Phys. Rev. C 88 (2013)

Orientation of the magnetic field

Magnetic field of a lead ion at LHC energy.



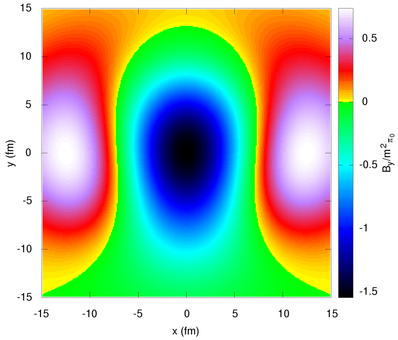


Magnetic field of *classic* origin, at $\tau = 0.2\,\mathrm{fm/c}$, $\eta = 0$, b=8 fm, $\sigma = 5.8\,\mathrm{MeV}$

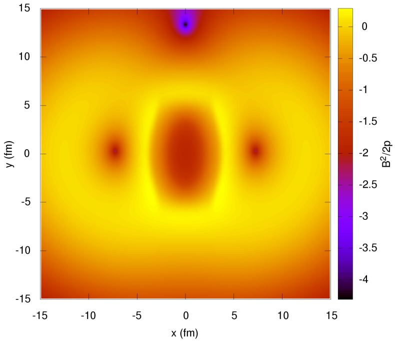
Magnetic field of *chiral* origin, at $\tau = 0.2\,\mathrm{fm/c}$, $\eta = 0$, b=8 fm, $\sigma_\chi = 1.5\,\mathrm{MeV}$ ($\nabla \cdot \vec{B} = 0$: $B_z \neq 0$ not plotted !)

Ratio between initial magnetic and thermal pressure

3D+1 simulation of Au+Au collision at $\sqrt{s_{\mathrm{NN}}} = 200\,\mathrm{AGeV}$
Conductivities of the medium ($\tau \leq \tau_0$): $\sigma = 5.8\,\mathrm{MeV}$, $\sigma_\chi = 1.5\,\mathrm{MeV}$

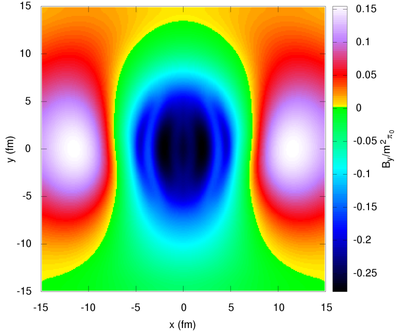


B_y at $\tau = 0.4\,\mathrm{fm/c}$ and $\eta = 0$

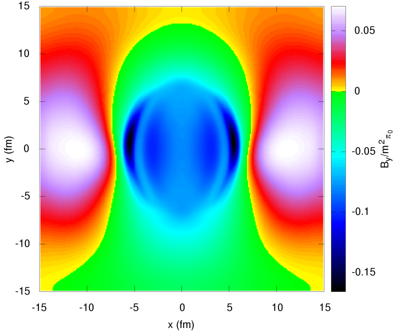


Magnetic/thermal pressure ratio

Magnetic field at later times

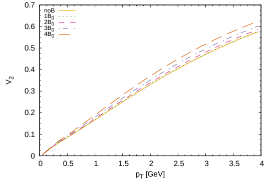


RHIC energy, b=12 fm, $\tau = 2\,\mathrm{fm}/\mathrm{c}$

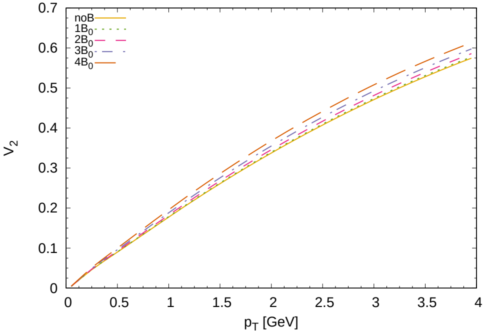


RHIC energy, b=12 fm, $\tau = 4\,\mathrm{fm}/\mathrm{c}$

Importance of the initial B magnitude

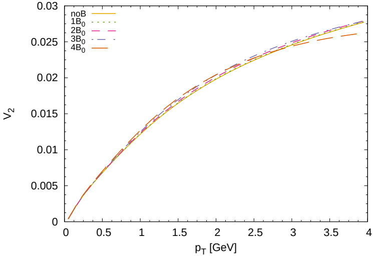


RHIC energy, b=12 fm

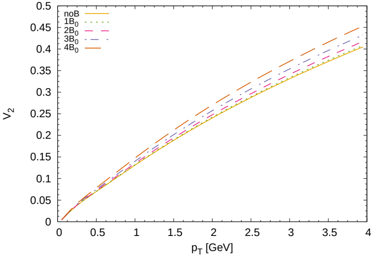


LHC energy, b=12 fm

$v2$ at different impact parameters

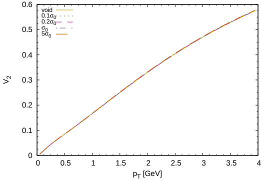


RHIC energy, b=2 fm

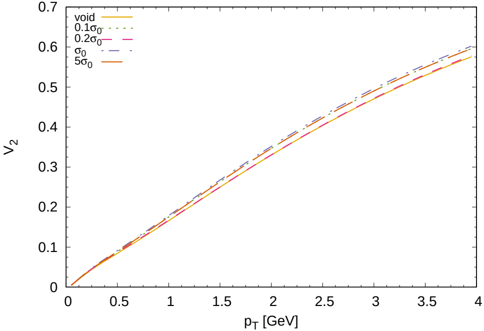


RHIC energy, b=8 fm

Impact of the initial conductivity



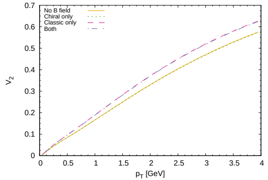
RHIC energy, b=12 fm



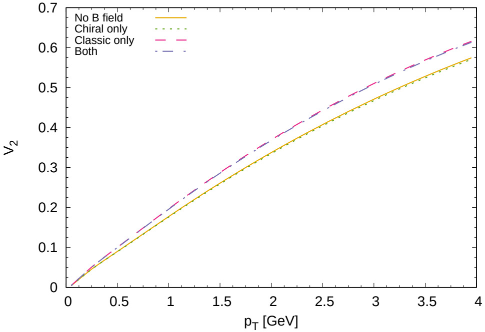
RHIC energy, b=12 fm, $B_{in.} = 3B_0$
Preliminary results, to be checked!

Separate effects of classic/chiral contribution

The magnetic field of chiral origin seems to play only a minor role (we are neglecting the dynamical evolution of axial currents).



RHIC energy, b=12 fm, $B_{in.} = 4B_0$



LHC energy, b=12 fm, $B_{in.} = 4B_0$

Final comments

- The impact of $\vec{B}$ on v_2 seems to be limited both at RHIC and LHC
- However, the many uncertainties in the pre-equilibrium phase might have led to an underestimate of the initial $\vec{B}$ field
- In this case, the magnetic field might produce an enhancement of v_2 in peripheral collisions
- But probably resistivity and viscosity strongly suppress this effect
- And hadronic rescattering might make measurements more difficult
- Moreover, assuming an initial null velocity field is a rough approximation
- Anyway, the basic MHD assumption $e^\mu = 0$ is not realistic: arXiv:1803.06695
- Moreover, we have seen in the talk by N.Tanji that $\mathbf{E} \cdot \mathbf{B} \neq 0$
- Eventually, taking into account EM fields in the Cooper-Frye (arXiv:1705.07842) prescription requires to go beyond ideal MHD

Future perspectives

- Ongoing collaboration (also with M. Kaminski) to include resistivity and dynamical evolution of axial charges (formalism almost completed by Y. Hirono, however numerical implementation might be challenging)
- Event by event simulations coupled with UrQMD (hadronic rescattering, resonances decay)
- Use of the γ correlator or the brand new $R_{\Psi_m}(\Delta S)$ (see R. Lacey's talk)
- Comparisons with $\vec{B}$ estimates based on $\Lambda - \bar{\Lambda}$ polarization splitting (see M. Lisa's talk)
- Connections with lattice QCD results (see M. D'Elia's talk)